

A COMMON ORIGIN FOR QUASAR EXTENDED EMISSION-LINE REGIONS AND THEIR BROAD-LINE REGIONS

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ABSTRACT

We present a correlation between the presence of luminous extended emission-line regions (EELRs) and the metallicity of the broad-line regions (BLRs) of low-redshift quasars. The result is based on ground-based [O III] $\lambda 5007$ narrow-band imaging and *Hubble Space Telescope* UV spectra of 12 quasars at $0.20 \leq z \leq 0.45$. Quasars showing luminous EELRs have low-metallicity BLRs ($Z \lesssim 0.6 Z_{\odot}$), while the remaining quasars show typical metal-rich gas ($Z > Z_{\odot}$). Previous studies have shown that EELRs themselves also have low metallicities ($Z \lesssim 0.5 Z_{\odot}$). The correlation between the occurrence of EELRs and the metallicity of the BLRs, strengthened by the sub-Solar metallicity in both regions, indicates a common external origin for the gas, almost certainly from the merger of a gas-rich galaxy. Our results provide the first *direct* observational evidence that the gas from a merger can indeed be driven down to the immediate vicinity (< 1 pc) of the central black hole.

Subject headings: quasars: emission lines — galaxies: evolution — galaxies: ISM — galaxies: abundances

1. INTRODUCTION

Massive ionized nebulae having characteristic dimensions of a few $\times 10$ kpc surround roughly half of the quasars that are also steep-spectrum radio sources at $z < 0.5$ (see Stockton et al. 2006a for a review). These luminous extended emission-line regions (EELRs) typically show complex filamentary structures that bear no close morphological relationships either with the host galaxies or with the extended radio structures (Stockton & MacKenty 1987), and chaotic kinematics uncoupled with the stars. There is accumulating evidence (Fu & Stockton 2006, 2007) that these EELRs comprise gas that has been swept out by a galactic superwind resulting from feedback from the quasar (e.g., Di Matteo et al. 2005). However, because the presence of a powerful radio jet seems to be a necessary (though not sufficient) condition for producing a luminous EELR, it is likely that the superwind is produced by a large-solid-angle blast wave accompanying the production of the radio jet (Fu & Stockton 2007), rather than by radiative coupling of the quasar’s luminosity to the gas.

The broad-line regions (BLRs) of quasars comprise material concentrated within ~ 1 pc of the central black hole (BH). Because of their proximity to quasar central engines and the accessibility of their emission lines, BLRs are the most widely used diagnostic for quasar abundances. The major metallicity indicators rely on line flux ratios involving nitrogen lines, due to the “secondary” nature of the element (Pagel & Edmunds 1981). Spectra of the BLRs, combined with photoionization models, show that most of the quasars are metal rich at all redshifts ($Z > Z_{\odot}$; Hamann & Ferland 1999; Nagao et al. 2006). Since quasars are usually hosted by high-mass galaxies, which typically have a high metallicity for their interstellar media (the mass—metallicity correlation; e.g., Tremonti et al. 2004), the high metallicity of quasars is not unexpected from the standpoint of normal galactic chemical evolution.

Simulations show that, during a galactic merger, the interstellar gas in the galaxies rapidly loses angular momentum, resulting in massive gas concentrations near the center of the merged galaxy (e.g., Barnes & Hernquist 1996). Hence, a

merger could potentially feed the BH and trigger an active galactic nucleus (AGN) or a quasar. If the current episode of quasar activity was triggered by a recent merger, and the EELRs were driven out by a superwind from the central part of the galaxy, then it is possible that there may be some relation between the gas in the EELRs and that in the BLRs. In this Letter we explore this possibility by comparing the BLR metallicity of quasars associated with luminous EELRs with those that do not show EELRs.

2. THE SAMPLE

We have compiled a sample of steep-spectrum radio-loud quasars that have both *Hubble Space Telescope* (HST) Faint Object Spectrograph (FOS) spectra covering the N V $\lambda 1240$ and C IV $\lambda 1549$ and/or He II $\lambda 1640$ lines emitted by the BLRs (hereafter N V, C IV & He II; Kuraszkiewicz et al. 2002, 2004), and [O III] $\lambda 5007$ narrow-band imaging data to detect or put upper limits on any EELRs associated with the quasar (Stockton & MacKenty 1987). We ended up with 6 objects that show luminous EELRs (the luminosity of the extended [O III] emission, $L_{[\text{O III}]}$ $> 5 \times 10^{41}$ erg s^{−1}; hereafter the “EELR quasars”), and 6 “non-EELR” quasars (3σ upper limits of $L_{[\text{O III}]} < 3 \times 10^{41}$ erg s^{−1}). Here, we have based the EELR luminosities on the “peak” luminosities given in Table 1 of Stockton & MacKenty (1987), since the upper limits to the “total” luminosities given there necessarily assume an unrealistically smooth distribution of emission. The quasar redshifts range from 0.2 to 0.45. The radio powers and spectral indices of the two subsamples are similar. Kuraszkiewicz et al. (2002, 2004) have given measurements of broad emission lines in the FOS spectra, from which we calculated the N V/C IV and/or N V/He II line ratios and estimated their 1σ uncertainty using the standard error propagation formula.

We have also obtained the absolute *B*-band magnitude ($M_{B,QSO}$) of the objects from Veron-Cetty & Veron (2006). The absolute *R*-band magnitude of the host galaxies ($M_{R,gal}$) is available for 6 of them, which have been imaged by HST WFPC2 with a broad-band filter (Labita et al. 2006). Using a formula based on the virial theorem (Labita et al. 2006), the black hole masses (M_{BH}) were estimated from the C IV FWHM and the continuum luminosity (λL_{λ}) at 1350 Å,

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TABLE 1
QUASAR SAMPLE

Designation (1)	Name (2)	z (3)	$M_{B,QSO}$ (4)	$M_{R,gal}$ (5)	$\log(M_{BH}/M_{\odot})$ (6)	$N\,V/C\,IV$ (7)	$N\,V/He\,II$ (8)
EELR Quasars							
1104+7658	3C 249.1	0.312	-25.2	...	8.96	< 0.010	< 0.046
1427+2632	B2 1425+26	0.366	-25.4	-23.2	9.73	< 0.015	< 0.073
1514+3650	B2 1512+37	0.371	-24.1	-23.2	9.22	$0.042^{+0.007}_{-0.005}$	$0.238^{+0.039}_{-0.031}$
1547+2052	3CR 323.1	0.264	-23.7	-23.1	9.10	< 0.012	< 0.056
2137-1432	PKS 2135-14	0.200	-24.2	-23.2	9.15	$0.037^{+0.008}_{-0.007}$	$0.423^{+0.097}_{-0.078}$
2254+1136	4C 11.72	0.326	-24.9	...	9.15	$0.033^{+0.083}_{-0.015}$	$0.190^{+0.477}_{-0.099}$
non-EELR Quasars							
0005+1609	PKS 0003+15	0.450	-25.1	...	9.24	$0.256^{+0.071}_{-0.006}$	$0.930^{+0.260}_{-0.038}$
0755+2542	OI-287	0.446	-22.9	...	7.47	$0.426^{+0.249}_{-0.135}$...
1052+6125	4C 61.20	0.422	-24.3	...	9.57	$0.157^{+0.069}_{-0.023}$	$0.903^{+0.414}_{-0.145}$
1153+4931	LB 2136	0.334	-22.9	-23.8	8.95	$0.174^{+0.023}_{-0.011}$	$0.808^{+0.112}_{-0.055}$
1704+6044	3C 351	0.372	-25.5	-23.7	9.15	$0.206^{+0.026}_{-0.021}$	$0.712^{+0.091}_{-0.086}$
2311+1008	PG 2308+098	0.433	-25.4	...	9.30	$0.274^{+0.021}_{-0.008}$	$1.427^{+0.123}_{-0.073}$

NOTES. — (1) Quasar J2000 designation, (2) common name, (3) redshift, (4) quasar absolute B -band magnitude (k -correction applied; converted from Veron-Cetty & Veron 2006), (5) host galaxy absolute R -band magnitude (after k -correction and passive evolution correction; following Labita et al. 2006), (6) black hole masses estimated from C IV FWHM and λL_{λ} at 1350 Å, using a formula based on virial method (Labita et al. 2006), (7, 8) UV emission line ratios and 1σ uncertainty (Kuraszkiewicz et al. 2002, 2004).

which are available from the modeling of the FOS spectra (Kuraszkiewicz et al. 2002, 2004). Our BH mass results are in agreement with those of Labita et al. (2006) within a factor of two. All of the data tabulated in Table 1 have been scaled to a Λ CDM cosmology with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 0.3$ and $\Omega_{\Lambda} = 0.7$.

3. RESULTS

Figure 1 shows that the EELR quasars and non-EELR ones are clearly separated by their broad-line ratios. $N\,V/C\,IV$ and $N\,V/He\,II$ flux ratios are predicted to increase substantially with metallicity in BLRs (Hamann et al. 2002). The validity of using these two line ratios as metallicity indicators has been confirmed by comparing results from other weaker nitrogen lines (Baldwin et al. 2003; Dhanda et al. 2007). Therefore, we conclude that the metallicity of the EELR quasars is systematically *lower* than that of the non-EELR quasars. Specifically, from a calibration of the line ratios in terms of metallicities (Nagao et al. 2006), the metallicity of the former group ranges from ~ 0.1 to $0.6 Z_{\odot}$, compared to 1 to $5 Z_{\odot}$ for the latter. The Solar elemental abundances are defined by Anders & Grevesse (1989).

On the other hand, the two groups look surprisingly similar in terms of other parameters, such as the redshift range, the quasar luminosity, the luminosity of the host galaxy and the black hole mass (refer to Table 1).

The EELR quasars are obvious outliers with respect to the observed metallicity—quasar luminosity correlation (Hamann & Ferland 1999; Nagao et al. 2006), or the purported metallicity—BH mass (Warner et al. 2003) and metallicity—accretion rate (Shemmer et al. 2004) relations ($\dot{M} = L/L_{edd} \propto 0.398^{M_{B,QSO}/M_{BH}}$). Furthermore, their low metallicity is also incompatible with the observed tight mass—metallicity correlation of normal galaxies (Pagel & Edmunds 1981; Tremonti et al. 2004), if the gas is from the interstellar medium of a galaxy as massive as the quasar hosts. Like normal AGN, the 4 (out of 6) EELR quasars for which the host galaxy luminosity were available follow the BH mass—bulge luminosity relation (Labita et al. 2006). Thus, if the co-evolution of galaxies and their central

black holes is indeed responsible for establishing this correlation, then for black holes of these masses, the accompanying star formation should have enriched the interstellar media in these galaxies to super-Solar metallicities. The observed low metallicity of the gas thus indicates that it originates *externally* to the quasar host galaxies.

The lower metallicity of the EELR quasars compared to the non-EELR ones implies some sort of link between gas in the close vicinity of a BH ($< 1 \text{ pc}$) and the material far out in the galaxy ($> 10 \text{ kpc}$). There is evidence that the EELRs also have a much lower metallicity when compared with the typical emission-line gas in an AGN. The optical line ratio $[N\,II] \lambda 6584/H\alpha$, when combined with $[O\,III] \lambda 5007/H\beta$, offers a convenient metallicity calibration for low-density gas photoionized by an AGN. This calibration has been used in the narrow-line regions of Seyfert 2 galaxies, and it has been shown to yield consistent metallicity with those extrapolated from nuclear H II regions (Storchi-Bergmann et al. 1998). The same calibration can be used to infer abundance for EELRs, since the EELRs are also photoionized and represent a similar density regime. For 3 of the 6 EELR quasars in our sample (1104+7658, 1514+3650, and 2254+1136), flux measurements for the key nitrogen line are available for their EELRs (Boroson & Oke 1984; Fu & Stockton 2006, 2007). The line ratios of all three EELRs are different from, and on the lower metallicity side of, most of the AGN narrow-line regions at similar redshifts. Specifically, the EELRs have a gas phase metallicity $Z \sim 0.5 Z_{\odot}$ (Stockton et al. 2002; Fu & Stockton 2006, 2007), and most AGN narrow-line regions have $Z > Z_{\odot}$ (Groves et al. 2006).

The correlation between the occurrence of EELRs and the metallicity of the quasar BLRs, reinforced by the similar metallicity of the EELRs and the BLRs, suggests a common origin of the two.

4. ORIGIN OF THE GAS

Cooling flows could in principle explain both the external origin and the sub-Solar metallicity of the emission-line gas of EELR quasars. However, this scenario in practice seems to have been ruled out by deep *Chandra* X-ray observations

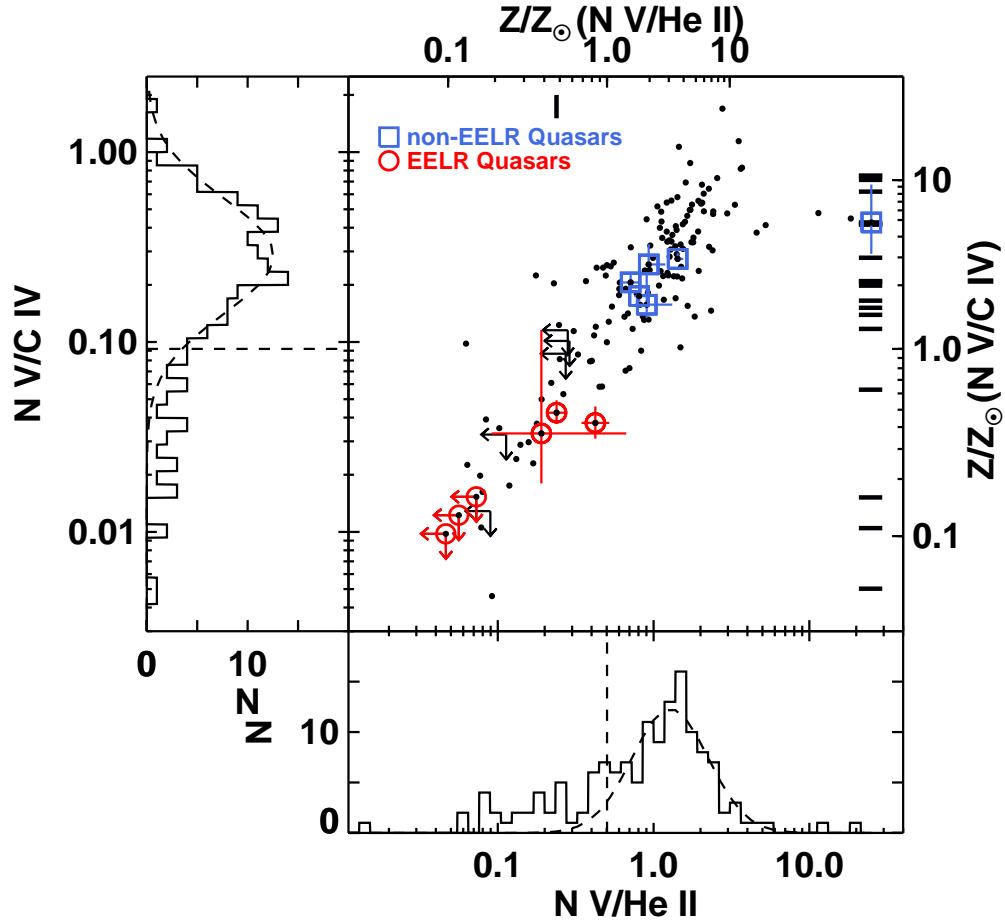


FIG. 1.— $N\text{ V/C IV}$ line ratios vs. $N\text{ V/He II}$ line ratios. The quasars in the *HST* FOS sample (Kuraszkiewicz et al. 2002, 2004) with measurements of all three lines are shown as black points and arrows (3σ upper limits) in the main panel. The bars aligned on the right and upper edges show the objects with only $N\text{ V/C IV}$ and only $N\text{ V/He II}$ ratios available, respectively. The EELR quasars are circled in red, and the non-EELR quasars are blue squares. The 1σ line-ratio errors are also shown for these objects. The metallicity predicted by the photoionization model (Nagao et al. 2006) appears across the right and top axes. Histograms of $N\text{ V/C IV}$ and $N\text{ V/He II}$ line ratios for all objects with solid measurements in the entire *HST* FOS sample are shown in the left and bottom panels, respectively. The dashed lines mark the Solar metallicity. Gaussian fits to the histograms are shown as dashed curves.

of four EELR quasars² (Stockton et al. 2006b), since the hot halo gas ($T \sim 10^7$ K) from which the warm emission-line gas is suggested to condense is not detected. Furthermore, a photoionization model (Stockton et al. 2002) of a representative EELR indicates that the clouds largely comprise a warm low-density medium, which has a pressure far too low to be in hydrostatic equilibrium with a hot external medium that would have a cooling time less than a Hubble time. Therefore, the merger of a gas-rich galaxy seems to be the most likely explanation for an external origin of the gas. Indeed, the disturbed morphology of the host galaxies of at least some EELR quasars (e.g., 3C 48, Canalizo & Stockton 2000; B2 1512+37, Stockton et al. 2002) clearly indicates ongoing mergers.

Assuming (1) the BH has built up most of its mass at a much higher redshift, (2) the current nuclear activity in these EELR quasars is triggered by a recent merger, and (3) both the EELR and the BLR have their origins in the interstellar gas of the incoming galaxy, we can put some constraints on the “intruder” based on the properties of the emission-line gas. The total ionized mass of a typical luminous EELR is $\sim 10^{9-10} M_\odot$ (Fu & Stockton 2006, 2007; in comparison, the BLR con-

tains a negligibly small amount of mass, with estimates ranging from 1 to $10^4 M_\odot$) and the metal abundance is about $1/2 Z_\odot$ or less. The intruding galaxy must therefore contain a substantial amount of metal-poor interstellar gas. The only types of galaxies we are aware of that potentially meet these requirements of substantial gas mass combined with low metallicity are the low surface brightness disk galaxies (e.g., van den Hoek et al. 2000) and perhaps some late-type spiral galaxies.

It is unclear why a merger of a more massive normal spiral, which may have a similar amount of gas (although a smaller gas fraction and a higher gas-phase metallicity), would not also produce an EELR. One possibility is that the higher metallicity will lower the accretion rate of material towards the center, because both the higher opacity of the gas and larger amount of dust will couple the gas more efficiently to the radiation field of the quasar. How such a lowered accretion rate will affect the development of the quasar is not certain, but, if it delays the formation of the radio jet, then much of the gas may have time to form stars before the jet is produced.

At the other end of the mass scale, if a merger with a gas-rich dwarf galaxy (e.g., a blue compact galaxy or an irregular galaxy) could also trigger a quasar, then any EELR associated

² Two of the four quasars are in our sample.

with this quasar would not have been in our sample, since the total mass of the interstellar gas would be below the detection limit of the EELR survey of Stockton & MacKenty (1987). However, the BLR would certainly be seen as having a low metallicity due to the accretion of the metal-poor gas by the BH. Therefore, the lack of detection of any metal-poor, non-EELR quasars implies that such mergers are not able to trigger a quasar (they may, however, trigger a low-luminosity AGN; Taniguchi 1999), probably because it takes too long ($>$ a few Gyr) to complete such a merger and most of the gas would have been stripped away by tidal forces and the ram pressure of the halo gas before the dwarf makes its way to the nucleus (Mayer et al. 2006).

Galactic merging has long been suggested to be a major mechanism for igniting nuclear activity in galaxies, since the interaction can bring fresh fuel close to the central BH. However, there exists only indirect evidence for the ability of mergers to deliver the gas sufficiently close to the nuclei to be accreted by the BHs (e.g., Zirbel 1996; Sanders & Mirabel 1996; Canalizo & Stockton 2001; Haehnelt & Rees 1993), and numerical simulations to date do not have sufficient dynamic range to explore such small scales. In the EELR quasars, the low metallicity of the gas in the EELR points to an external origin, most likely from the merger of a gas-rich galaxy. The correlation in metallicity between the gas at large scales and that in the BLR then provides the first *direct* observational evidence that the gas from a merger can indeed be driven down to the immediate vicinity of the central black

hole.

There has been much recent discussion on the relative importance of “quasar mode” and “radio mode” feedback in controlling galaxy formation and establishing the bulge-mass—BH-mass correlation. Quasar-mode feedback is usually envisioned as the radiative coupling of some of the energy output of a quasar to the surrounding gas, which expels the gas and quenches further star formation in the forming galaxy (e.g., Hopkins et al. 2006). Radio-mode feedback involves the prevention of surrounding gas from cooling sufficiently to form stars by the thermalization of the mechanical energy of radio jets (mostly FR I; e.g., Best et al. 2007). Our results suggest that there may also be a place for a variant of radio-mode feedback, operating exclusively in FR II radio sources, in which a wide-solid-angle blast wave from the production of the radio jet impulsively sweeps out a large mass of gas, in a manner quite similar to that envisioned for quasar-mode feedback. Because of the peculiar and poorly understood limitation of this mode to low-metallicity gas and the likely need for a BH that has already acquired a substantial mass, it might seem that this mechanism may have limited applicability in the early universe. Nevertheless, it is not unreasonable that such a scenario could occur rather frequently during the formation stage of the most massive galaxies.

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